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Proposal for the Design of a Zero Gravity Tool Storage Device

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Astronauts frequently use a variety of hand tools during space missions, especially on repair missions. A toolbox is needed to allow storage and retrieval of tools with minimal difficulty. The toolbox must contain tools during launch, landing, and on-orbit operations (Bourell, p. 1). The toolbox will be used in the Shuttle Bay and therefore must withstand the hazardous space environment. The three main functions of the toolbox in space are: to protect the tools from the space environment and from damaging one another; to allow for quick, one-handed access to the tools; and to minimize the heat transfer between the astronaut's hand and the tools. This proposal explores the primary design issues associated with the design of the toolbox. Included are the customer and design specifications, global and refined function structures, possible solution principles, concept variants, and finally design recommendations.

Scope and Limitations

Background and Clarification of Task

The tool storage device will be located in the Shuttle Bay near the midsection of the bay as seen in Figure 1. The device will attach to the wall by interfacing with the Extended Adaptive Payload Carrier (EAPC) through the attachment holes provided. Appendix A gives the dimensions and geometry of the EAPC. The tools to be stored in the device are described in Appendix B.

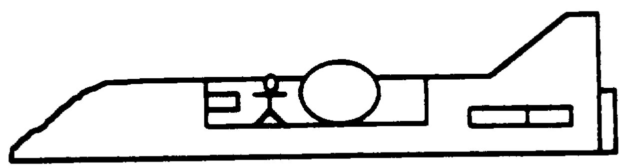

Figure 1. Tool storage device located in the Shuttle bay.

The task is to design a zero gravity toolbox which will allow storage and retrieval of tools with minimal number of operations for the user. Retrieval of tools can only require the use of one hand because the astronaut must secure himself while applying forces. The toolbox must be designed to minimize heat transfer from an astronaut's hand, through the glove, and into the toolbox (Bourell, p. 1).

The problem statement contains two biases. First, by referring to the design as a toolbox the customer is implying that a rectangular cover will be used to protect the tools, but protection of tools can be accomplished by a variety of shapes and materials. The second bias in the problem statement is the minimization of heat transfer. The astronaut's hand will lose thermal energy to radiation independent of any objects he/she contacts. The thermal energy lost to the tool storage device from the hand is lost through conduction from the hand into the device. Since the scope of this paper is limited to the design of the tool storage device and not the design of the astronaut's glove, only the heat transfer characteristics of the device are relevant. The heat transfer relation governing conductive losses is given by

$$q = q(k, c, \rho, t)$$

where k is the thermal conductivity of the device, c is the specific heat of the device, ρ is the density of the material, and t is time. To reduce the heat transfer from the astronauts hand to the tool storage device, any one or a combination of these parameters should be reduced (Vliet). Material designation will not be made until the embodiment stage of the design process and is out of the scope of this proposal; therefore, the focus of this document will be minimizing the time of contact between the device and the user.

Design Issues

When considering designs for the tool storage device, there are several issues which must be addressed. Reducing heat loss from the astronaut's hand may be accomplished without changing the current tool storage device. For example, the materials of the glove could be changed to reduce conductive losses between the glove and the device. The amount of time spent holding the tool is much greater than the time the astronaut is in contact with the device. As a result, changing the conductive properties of the tools would reduce heat loss from the hand. In general, the heat is always transferred from the astronaut to the device. The device exceeding an upper temperature limit is not a problem (Norrell). The scope of this document does not include the design of the glove or tools. Because the tools vary in size, all tools may not be secured in the same manner. For example, clips may have to be provided in a variety of sizes to account for the differences in the tool geometries. While primary securing devices are chosen for the concept variants, secondary securing device may be necessary for specialized tools. Ergonometric standards set by National Aeronautics and Space Administration (NASA) must be accommodated for in the design of the tool storage device because the device must be operable by an astronaut wearing an external mobility unit (EMU). Because of the zero-gravity conditions, friction is not acting to keep the astronaut in place while applying a force. A NASA standard hand hold or foot securing device must be provided to anchor the astronaut while he/she applies forces.

Specifications

The specifications of the zero gravity tool storage device are listed in Table 1. This list incorporates the customer requirements along with specifications introduced by the design team. The specifications ensure the proper operation of the system. The more important specifications are discussed.

Table 1

Specification List

Customer NASA		SPECIFICATION for: Zero Gravity Tool Storage Device	Page 1
Date	**D/W**	**Requirements**	**Test or Verification**
3/6/94		**Functional Requirements**	
	D	Contain tools during launch, landing and orbit operations	Review design
	D	Secure tools not currently in use	
	D	Minimize heat transfer between the device and the astronaut's hand	Heat transfer calculations
	D	Functional in pressurized and vacuum environments	Simulate conditions
	D	Allow quick retrieval or storage of tools (< 30 seconds)	Time procedure
3/6/94		**Geometry**	
	D	Interface with the Extended Adaptive Payload Carrier	Verify dimensions
3/20/94	W	Minimize volume (<0.75 cubic meters)	Analytical calculations
3/20/94	W	Maximum dimensions: (45cm x 25cm x 100cm)	
3/6/94		**Kinematics**	
	D	Use friction hinges for zero gravity use	Review design
	D	Use magnetic locks for temporary closing	
	D	~~Secure latches for takeoffs and landings~~	
	D	~~Provide device to hold box open when desired~~	
3/6/94		**Forces**	
	D	Maximum weight exclusive of tools: 235 pounds	Mass calculations based on geometry and material properties
	D	Withstand acceleration forces at launch and landing (up to 12.5G)	Finite element analysis on parts
	W	Force applied by astronauts comply with ergonometric data (e.g. 1 psi for 30 seconds without discomfort)	Human Factors Handbook
	D	Natural frequency with respect to orbiter attachment < 30Hz	Dynamic simulation
3/6/94		**Energy**	
	D	Available power storage	Review design
	D	Do not consume any power from the space shuttle system	
	D	Passive cooling as in NASA standards	
	W	Power requirements: < 1000 Watts	Power calculations
	W	Natural energy consumption	Review design
3/6/94		**Material**	
	D	Withstand repeated impact of micrometeoroids (up to .01mm diameter, 20 Km/sec)	Impact simulation
	D	Resist embrittlement	Verify material properties
	D	Resist pressure changes from atmosphere to vacuum (up to 9psi per minute)	
	D	Avoid radioisotopes both natural and unnatural (radioactive materials)	
	D	No toxic gases discharged to mid-deck environment	
	W	Minimize mass	
3/8/94	D	Surface temperature maintained between -120 and 113 degrees C	
3/6/94		**Signal**	
	W	Stored energy level indicator (0-100%)	Review design
3/8/94	W	Provide temperature reading	

Table :
(Continued)

Customer NASA		SPECIFICATION for: Zero Gravity Tool Storage Device	Page 2
Date	D/W	Requirements	Test or Verification
3/6/94		**Safety**	Compare design with NASA 's EVA safety standards
	D	No sharp edges or corners on box (as established by NASA's System Description and Design Data)	
	D	Avoid knurled surfaces which may cause abrasion to EMU	
	D	Conform to fire safety standards (if power sources are used for toolbox)	
3/6/94		**Ergonomics**	
	D	Operations performable with EMU	Simulate procedure using an EMU
	D	Allow one handed opening and closing of any latches or doors	
	D	One handed removal or storage of tools	
	D	Switches or knobs operation with low force gross motor activity	
	D	EVA Handles must conform to minimum IVA handle dimensions (Man System Integration Standards)	
	W	Non-slip handles	
3/6/94		**Assembly**	
	D	Secure tools before shuttle is launched	Review procedures
	D	Provide for attachment to EAPC (e.g. bolts, rivets)	Verify dimensions
3/8/94	D	Mount EAPC and toolbox in shuttle payload bay near the middle at all times	Verify mounting
3/6/94		**Operation**	
	D	Operate in environment temperature of -100 degrees C	Creep test
	D	Withstand radiation levels of 1200 W/ m^2	Estimate absorptivity
	D	Operational in zero gravity	Simulate operating conditions
	D	Operational in a vacuum	
	W	Life cycle of 5 years	
3/6/94		**Maintenance**	
	W	Maintenance free	Review Design
	D	Any lubricants needed must conform to standards	
	W	Schedule preventive maintenance	
		Transportation	
3/8/94	D	Attached to EAPC and shuttle payload bay at all times	Review procedures
3/8/94	D	Tools stored in toolbox for the duration of mission	
3/8/94		**Quality control**	
	D	Test prototype to verify operation	
3/8/94		**Cost**	
	W	Minimize cost based on number of devices, and high precision manufacturing	Cost of manufacturing processes
3/8/94		**Schedule**	
		Refined function structure (March 11)	
		Proposal (April 1)	
		Embodiment design (1 year)	

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Functional Requirements

The tool storage device must be mountable to the EAPC. Once mounted to the EAPC, the tool box will remain in place until the mission is over and the shuttle is back on Earth. There will be no separate carrier for the tools during extended storage or transport. The tools contained in the device must remain securely in place at all times.

In past missions, the astronauts had to manipulate the toolbox to withdraw a tool. Consequently, their hands became very cold which was uncomfortable and often resulted in a temporary loss of manual dexterity. In order to prevent this problem, the device must be designed to minimize heat transfer with the astronaut's hand. The expression governing the amount of heat transfer is a function of time; therefore, reducing the contact time directly affects the amount of heat transfer.

Geometry

The final design of the tool storage device must be attachable to the EAPC. There are no total volume restrictions, but the face attached to the EAPC must not exceed 114 cm. x 64 cm. (45" x 25"). The maximum volume requirement is 0.75 m^3. This volume was chosen by approximating the depth of the device as the length of an average arm, 100 cm.

Kinematics

Any opening doors or lids included in the design must include friction hinges for zero gravity use and magnetic locks for temporary closing (*Shuttle/Payload*, p. 5-2). Secure latches for takeoffs and landings must be provided. The design must also provide for a hold-open device.

Forces

A device designed for transport to and from space must withstand the effects of significant forces. The forces due to the accelerations at launch and landing may reach values of 12.5 g's (*Shuttle/Payload*, p. 4-1). The structure of the device should be designed ~~according to the expected stresses and strains~~.

The maximum allowable weight for the device exclusive of tools is 235 pounds. Furthermore, forces or torques needed to operate the device must conform to ergonometric requirements established by NASA. Tables containing this information can be found in pages 4-11 through 4-16 of the "Man System Integration Standards."

Energy

If the system requires a power source, this power must be independent from the power source supplying the space shuttle. The power requirements of the system must be under 1000 Watts based on the power requirement of similar equipment used in previous missions (Asker, p.25).

Material

When selecting a material for the tool storage device, there are several issues to consider. Since the toolbox is going to be exposed to the hazards of space while being used in the Shuttle Bay, the material must be able to resist rapid pressure changes from atmospheric to vacuum environments. A maximum rate of 9 psi per minute has been established by NASA (*Shuttle/Payload*, p. 6-1). The material must be able to withstand repeated impact of micrometeroids which have diameters up to 0.001 mm and move at speeds as high as 20 km/sec (Benaroya, pp. 6-11). Based on the existing design of the EMU glove, NASA has established that surface temperatures of objects coming in contact with the EMU be between -120 °C and 113 °C (*Man System*, p. 14-12). In addition, any material used in the embodiment of this project must conform with NASA's NSB1700.7 Materials Specifications. Radioactive and toxic materials must be avoided (*Shuttle/Payload*, p. 5-1).

Safety

Since the astronauts will be in close contact with the device, it is imperative there is no risk of abrasion to the EMU suit. The tool storage device must not have knurled surfaces nor sharp corners or edges on the external surface (*System Description*, p. 11.2-8).

Ergonomics

Any operation related to the system has to be performable by an astronaut wearing an EMU. Extravehicular activities (EVA) require a clearance of 6 cm. around handles and tools (*Man System*, page 11-6).

In order to minimize the contact between the astronaut and the system, opening and closing of doors or latches must be a one handed operation. One handed operation allows the astronaut to secure himself. Removal and storage of tools must also be a one handed operation.

Requirements for the dimensions of handles used in EVA's are the same as for intravehicular activities (IVA). IVA handle dimensions are given in the *Man System*

Integration Standards, p. 11-23. These handles must also be made of a non-slip material to provide a proper grip for the astronaut.

Assembly

The design of the tool storage device must provide an attachment to the EAPC. The device must be mounted to the EAPC in the middle of the shuttle payload bay for the duration of the flight (Figure 1). The tools must be secure inside the tool storage device prior to launch to prevent the tools from moving around.

Operation

The tool storage device must be operational in the space environment. In low orbit operations the temperature averages -100 °C, and the pressure is 0.00003% of atmospheric pressure (Battan, p.29). Furthermore, equipment is exposed to direct solar radiation. This radiation ~~has a~~ value of 1353 Watts/m^2 (Incropera, p. 750).

Functional Description

Process Description

A complete process description of the tool storage device involves preparation, execution, and conclusion phases. Table 2 shows the functions contained in each of these three phases.

The tool storage device must be prepared for operation. Before the Space Shuttle launch, the device is assembled, and the standard tools are secured in the tool storage device. After assembly is completed, the device is mounted to the EAPC for storage in the Shuttle bay. The EAPC is interfaced with the device and mounted in the midsection of the Shuttle bay. The storage device must be secured for launch in accordance with NASA specifications to prevent damage to the device and the Shuttle bay. Securing the device ensures proper transportation of the device during the shuttle mission. When tools are required for a repair mission, the user confirms the energy storage level, the energy source, and the temperature of the device only if the device requires a power source. Confirming these operations of the device establishes that the device is functioning correctly.

Table 2

Process Description

Preparation	Execution	Conclusion
assemble device place standard tools in device mount device to EAPC mount EAPC to shuttle bay secure device for launch check energy storage check energy source check device temperature	interface device with EAPC minimize heat transfer support storage device measure temperature store energy convert energy If retrieving tool: indicate position of tool orient tool for access expose tool join tool with hand If replacing tool: indicate position of tool clear path to tool location resecure tool in proper position protect tools	secure device for transport clean device make required repairs store for further use

During the execution phase the tool storage device executes different subfunctions. Operations that occur at all times during the function of the storage device are non-unique. These non-unique functions are minimizing the heat transfer between the glove and the tool storage device and supporting the structure of the device. The tools are protected by the external structure of the device to prevent damage to the tools from the hazards of space. If energy is required, the device will store and convert useful energy and measure the temperature of the device. In this case, measuring the temperature of the device is a non-unique function. If a tool is to be retrieved, the device indicates the position of the selected tool, orients the tool for access, exposes the tool to the user, and joins the tool with the hand of the user. If a tool is to be replaced, the device indicates the storage position of the tool, clears a path to that position, and resecures the tool until the tool is retrieved again

After the execution phase has been completed, the storage device will be secured in the Shuttle bay for transportation. If the device is utilized again before the mission is over, some of the preparation phase and all of the execution phase will be repeated. If the mission is ending, the device will be secured for landing. After each mission, the device should be cleaned, repaired, and stored for further use.

System Boundaries

Temporal Boundaries

The temporal boundary of the system encompasses the execution phase of the process description displayed in Table 2. In addition, measuring the energy storage level and temperature are functions contained in the system boundary. After the tools are placed in the device during the preparation phase of the process, the tools remain in the system boundary unless removed by the astronaut. The remaining preparation functions and the entire conclusion phase are excluded from the system.

Spatial Boundaries

The physical structure of the tool storage device, the stored tools, the attachments on the device such as knobs or levers, the EAPC, and the EAPC mounting bolts are included in the spatial boundaries of the system. Spaces created during the use of this device are also included. Figure 2 presents an explanation of the system boundaries. The astronaut's hand becomes part of the system when a tool is physically removed or replaced. Otherwise, the astronaut is excluded from the spatial boundaries. The decisions of the astronaut are made externally and enter the system as signals. The support structure provided to anchor the astronaut is not contained in the spatial boundaries because support structures do not aid the primary function of storing tools.

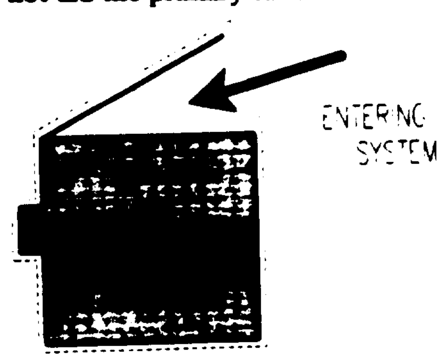

Figure 2. Spatial boundaries defined for the tool storage device.

Function Structure

The black box shown in Figure 3 describes the primary function of the zero-gravity tool storage device. The primary function is to store the tools needed for space missions. Energy enters the system as human power, cosmic radiation, and conducted heat. Energy in the form of radiated heat exits the system. The materials entering or exiting the system are the user's hand and the selected tool. The tool choice and the decision to retrieve or replace a tool are the signals entering the system, and the exiting signals are the temperature of the box and the stored energy level.

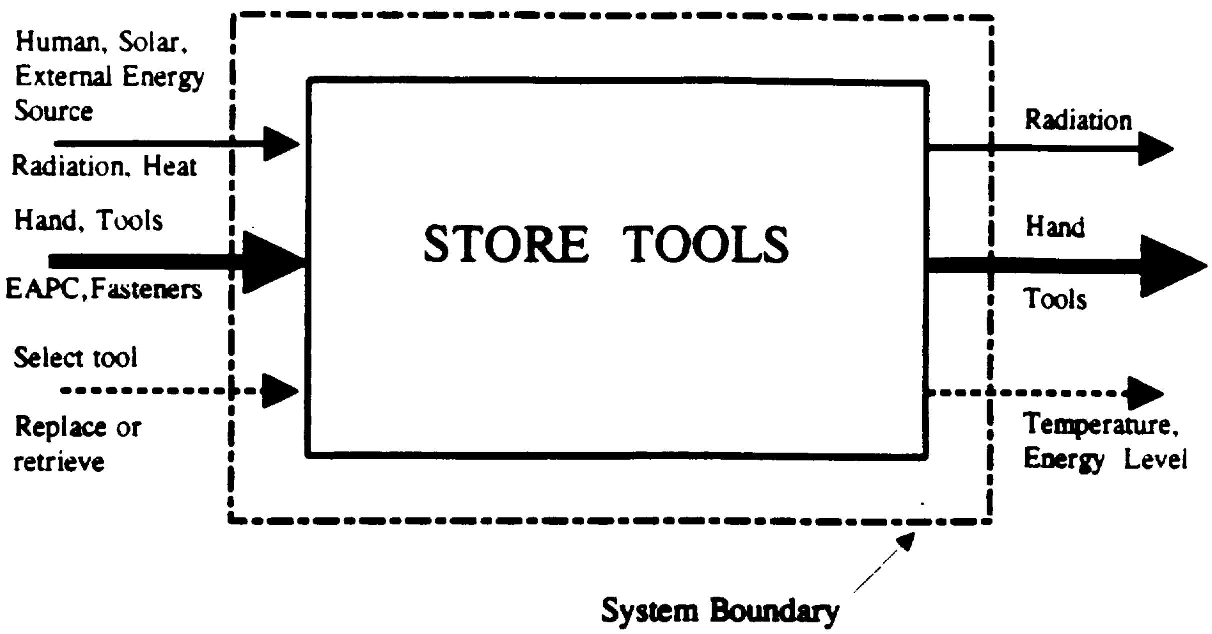

Figure 3. Overall function structure for the tool storage device.

The global function structure in Figure 4 shows the subfunctions of the tool storage device. The dashed line surrounding the diagram defines the system boundary. The first functions of the device are to store and convert the energy. The dashed lines around these subfunctions represent that these functions are auxiliary. These auxiliary functions may or may not be necessary to the operation of the device. Power requirements may complicate the system design and result in an unsafe device.

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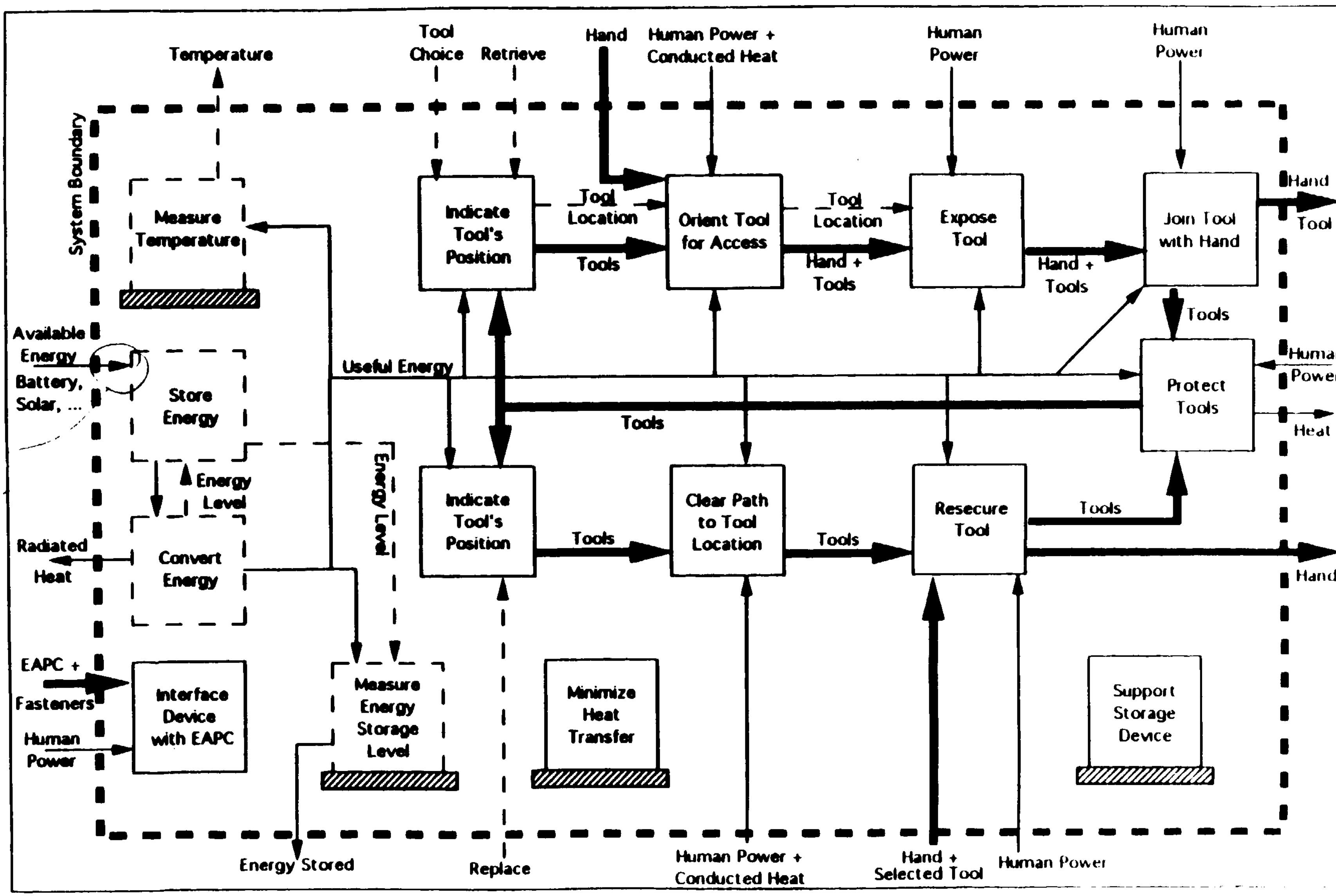


Figure 4: Function Structure: Zero Gravity Tool Storage Device

During the operations of the tool storage device, the device will perform several subfunctions continuously. The system minimizes the heat transfer from the user to the device by minimizing the contact time between the user and the device. If the device uses an external energy source, the stored energy level and the temperature of the device will be continuously measured. In addition to the above functions, the system provides support for the storage device.

The user will make a decision to retrieve a tool or to replace a previously selected tool. If the signal into the system is to retrieve a tool , the device indicates the position of the selected tool. After the tool location has been established, the device or the user orients the tool for access. If the tool is in a position to be accessed by the user, a function to orient the tool for access may share functions with exposing the tool to the user. Exposing the tool to the user positions the tool to prevent astronaut contact with the device. The astronaut's hand grips the tool, and the hand joined with the selected tool exists the system. If a signal to replace the tool enters the system, the storage position of the tool is indicated to the user. The path to the storage location is cleared to remove obstructions. Once the path is clear, the hand and selected tool enter the system. Then, the tool is resecured in the proper position, and the user's hand leaves the system. The preceding functions may expose the tools to the environment; therefore, the tools may be unprotected temporarily. After a tool has either exited the system or been resecured in the system, the tools contained in the device are protected. Power from the user or an outside source may activate the protective component of the tool storage device.

Solution Principles

From the function structure six critical subfunctions have been identified: indicating the tool's position, orienting the tool for access, exposing the tool, protecting the tools, securing the tools, and minimizing heat transfer. These subfunctions satisfy the design requirements of the customer. For example, before the astronaut's hand can enter the system and be joined with the tool, the device must expose the tool to the user. The following sections summarize the solution principles found for each of the subfunctions and the relevance of each principle to the design requirements.

Table 3 presents the results of the search for solution principles for each of the subfunctions. These solution principles were created in a brainstorming session using intuitive and discursive biases. For example, a rotating device similar to a Rolodex was intuitively created to store the tools and allow retrieval. Using a discursive method, this idea was slightly altered, and conveyor solution principle resulted. Next, the solution

Table 3
General Morphological Matrix

Category / Subfunction	Rotational	Translational	Stationary	Requires Power Source
Indicate Tool's Position		Spring System	Map/chart/label Tranparency No exterior cover Window	Electronic indicator Audio
Orient Tool for Access	Carrousel Track Conveyor Crank Smooth knob Knurled knob	Magnets Springs J bar T bar U Handle	Manually	Robotic system
Expose Tool	Roll top	Open box -hand -foot Tray Eject mechanism	No lid Screen Incubator system	Remote control Robotic arm
Protect Tool			Box Tool pouches Resistant material Polymers	
Secure Tools	Screws Vice grips		Mold Pins Tray Shelves Bungee cords Adhesives Latches Snaps Individual pouch Hooks Magnets Velcro Clips Leash Tie down	
Store Energy				Electrical Battery Solar Refrigerant flow Fluid Radiation
Minimize Heat Transfer			Minimize time Material Insulation	

principles for the important subfunctions were analyzed. Table 4 is a morphological matrix which illustrates the solution principles that were analyzed in detail.

Storing Energy

Storing energy is important to provide necessary power for the device to operate. Because the use of energy may not be required for the storage device to function, storing energy is an auxiliary function. Ideally, the tool storage device should not require an energy source. Battery power, solar energy, radiation other than solar, hydraulic power, and electrical power are methods to provide energy to the device. NASA uses batteries as energy sources on the Shuttle.

Indicating Tool's Position

The design decisions for the tool storage device are based on the specification of minimizing contact time between the user and the tool storage device. By indicating the position of the tool before the user makes contact with the device, the retrieval time and contact time are decreased. For this reason, indicating the position of the tool is a critical subfunction.

Several solution principles for indicating the tool's position were created. A window or transparent box would allow the user to see where the tool is located. If a hard cover does not enclose the tools on all sides, the astronaut visually locates the position of the tool through the opening. Labels and charts would also display the location of each tool. A number pad with designated number codes for each tool is a type electronic chart. The user enters the number code and the position of the selected tool is displayed.

Orienting the Tool for Access

Orienting the tool positions the tool for access by the astronaut's gloved hand. Clearances around the tool must allow the glove to encompass the tool. If the tool storage device orients the tool for access, the user would not have to search for the tool with his/her hand. Since the astronaut will be in an EMU suit, movement and dexterity are impaired by the gloves. Consequently, the astronaut has difficulty maneuvering the tools. Orienting the tool for access is a critical subfunction because contact time between the user and the tool storage device is decreased and the required clearances are provided.

The solution principles considered for this subfunction are shown in Table 4. The conveyor principle originates from a Rolodex. A Rolodex orients an information card for access by rotating the card into a position to be read. At a dry cleaning store, a track is

Table 4

Morphological Matrix

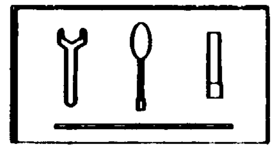
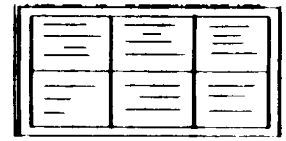
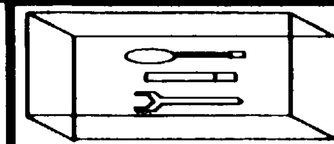
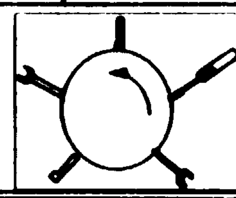
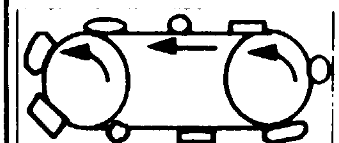
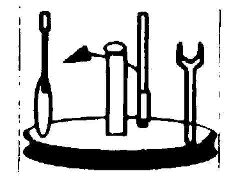
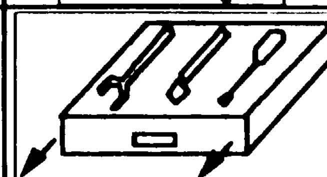
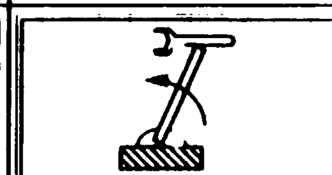
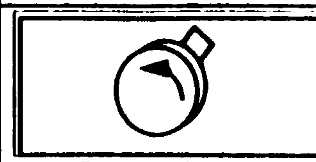
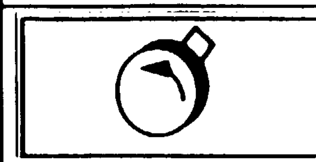
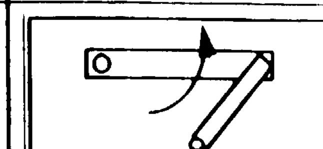
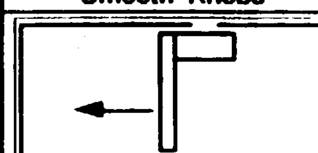
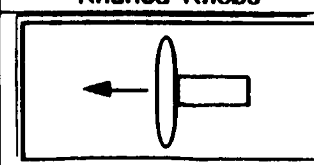
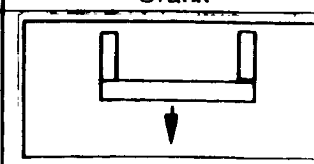
Subfunction \ Solution Principles	Category	1	2	3
Indicate Tools Position	Visual Aids	 Diagram	 Chart	
	Visuals	 Transparent Container	 Window	 Open Sight Line
Orient Tool for Access	Mechanical			
				
	Rotational Knobs	 Smooth Knobs	 Knurled Knobs	 Crank
	Translational Handles	 J Bar Handle	 T Bar Handle	 U Bar Handle

Table 4
Morphological Matrix
(Continued)

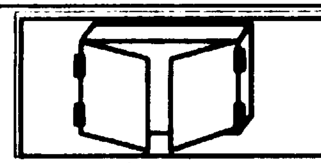
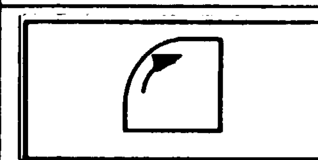
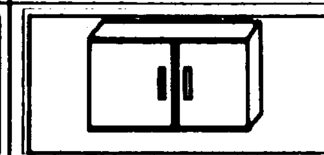
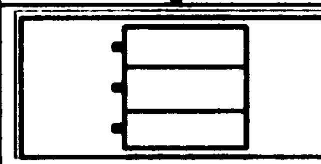
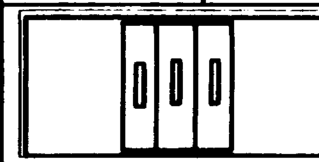
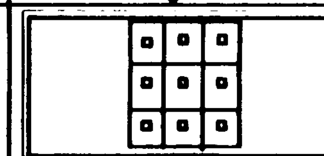
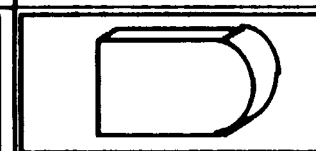
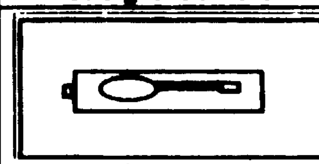
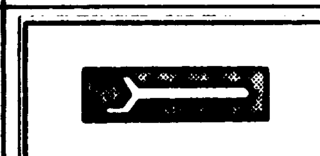
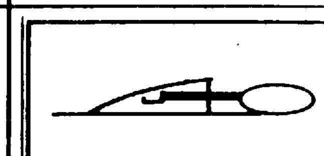
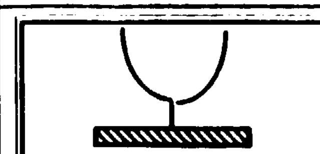
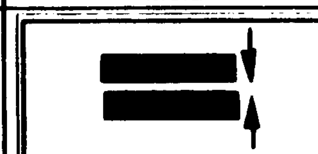
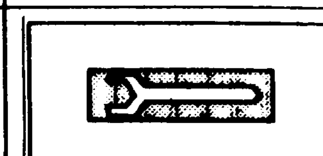
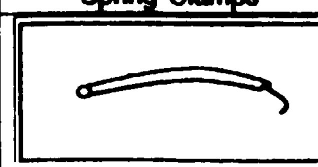
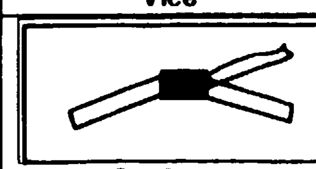
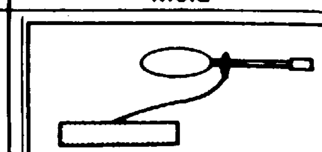
Subfunction / Solution Principles	Category	1	2	3
Expose Tool	Opening Doors	 Hinges	 Rolltop	 Sliding Doors
	Drawers	 Horizontal	 Vertical	 Individual
Protect Tool	Encompassing Shell	 Straight Corners	 Rounded Corners	
	Individual Protector	 Drawers	 Mold	 Pouch
Secure Tool	Clamps	 Spring Clamps	 Vice	 Mold
	Tether	 Bungee Cord	 Tie Down	 Leash

Table 4
Morphological Matrix
(Continued)

Solution Principles / Subfunction	Category	1	2	3
Minimize Heat Transfer		 Minimize Time	k c_p ρ Material Properties	$\Delta T = T_h - T_b$ Minimize Temp Differ

used to orient the dry cleaning for access. A lever orients tools for access by tilting the tool into an upright position and providing enough space for the astronaut to grip the tool.

Exposing Tool

Exposing the tool is critical to the function of the device because the path to the tool must be unobstructed to join the tool with the astronaut's hand. If the tool is not exposed to the user, the contact time is increased to maneuver the tool out of the device. Exposing the tool provides the required clearance to join the astronaut's hand with the tool. Orienting the tool for access and exposing the tool can be combined into one solution principle that shares both functions.

Joining Tool With Hand

Joining the hand with the tool to be removed from the system is the last step in the process of tool retrieval. One solution principle is for the astronaut's gloved hand to enter the system and grab the tool. Since the tool must be placed in the hand due to safety considerations, other solution principles were not considered. The tool is placed in the astronaut's hand to decrease the contact time with the system. For example, the tool may be ejected from the storage device; therefore, the user would not have to enter the system boundary to retrieve the tool. However, the user should be in position to receive the tool.

Protecting Tools

Protecting the tools is a critical subfunction because the customer requires that the tools be protected from the extreme environmental conditions of space. These conditions include cold temperature extremes and pressure changes. An external shell could protect all of the tools at once, or individual covers could protect each tool. The external cover could be a box or a rounded container. An individual drawer or pouch can protect an individual tool or a group of tools. Molds can also protect the tools.

Securing Tools

Securing tools is a critical subfunction. Holding the tools in place prevents tools from floating away and contacting the device structure. If the tools contact the device, damage to the device or tools could result. A solution principle can simultaneously protect and secure the tool. Devices used to secure the tools include tethers and clamps. Bungee cords tie downs and leashes are tethering devices while vice grips, spring clips, and molds are examples of clamps.

Minimizing Heat Transfer

Minimizing heat transfer is an important subfunction since NASA requires that the tool storage device prevent heat loss from the hand. Solution principles for minimizing heat transfer include minimizing contact time, material thermal properties, and temperature differences between the hand and the device. Since minimizing heat transfer is a continuous function of the storage device, minimizing heat transfer will be used as a criteria to judge solutions.

Interfacing with EAPC

The device must attach to the EAPC for storage in the Shuttle bay. Because NASA pre designates how the device and EAPC must interface, possible solutions will be judged on ability to interface with the EAPC.

Design Alternatives

Concept Variants

Solution principles were combined to produce three different concept variants. To decide which solution principles to combine to form the concept variants, principles that could share functions and complement each other were chosen. By choosing principles that could share functions, the concepts require fewer elements; therefore, the number of operations performed by the user is reduced.

Concept Variant 1: Tool Box with Drawers

The first concept variant is a square box with drawers that contains tools. The concept for this design is shown in Figure 5. The box has several drawers stacked one above the other. The tools are divided and placed in a drawer according to space and clearance requirements. Drawers have one runner along the bottom of the drawer. Each drawer has a handle that allows the astronaut to open the drawer with one hand.

Inside the drawers, the tools are secured in moldings of each tool while ~~ix~~ tools are not in use. The mold secures the tools on both ends while allowing open space around the center of the tool for the astronaut to grasp the tool without touching the box as in Figure 5. The mold material should be able to withstand the extreme environment and not expand due to temperature changes. Relative thermal expansion coefficients are critical to ensuring proper tool security. Material properties of the mold are therefore important.

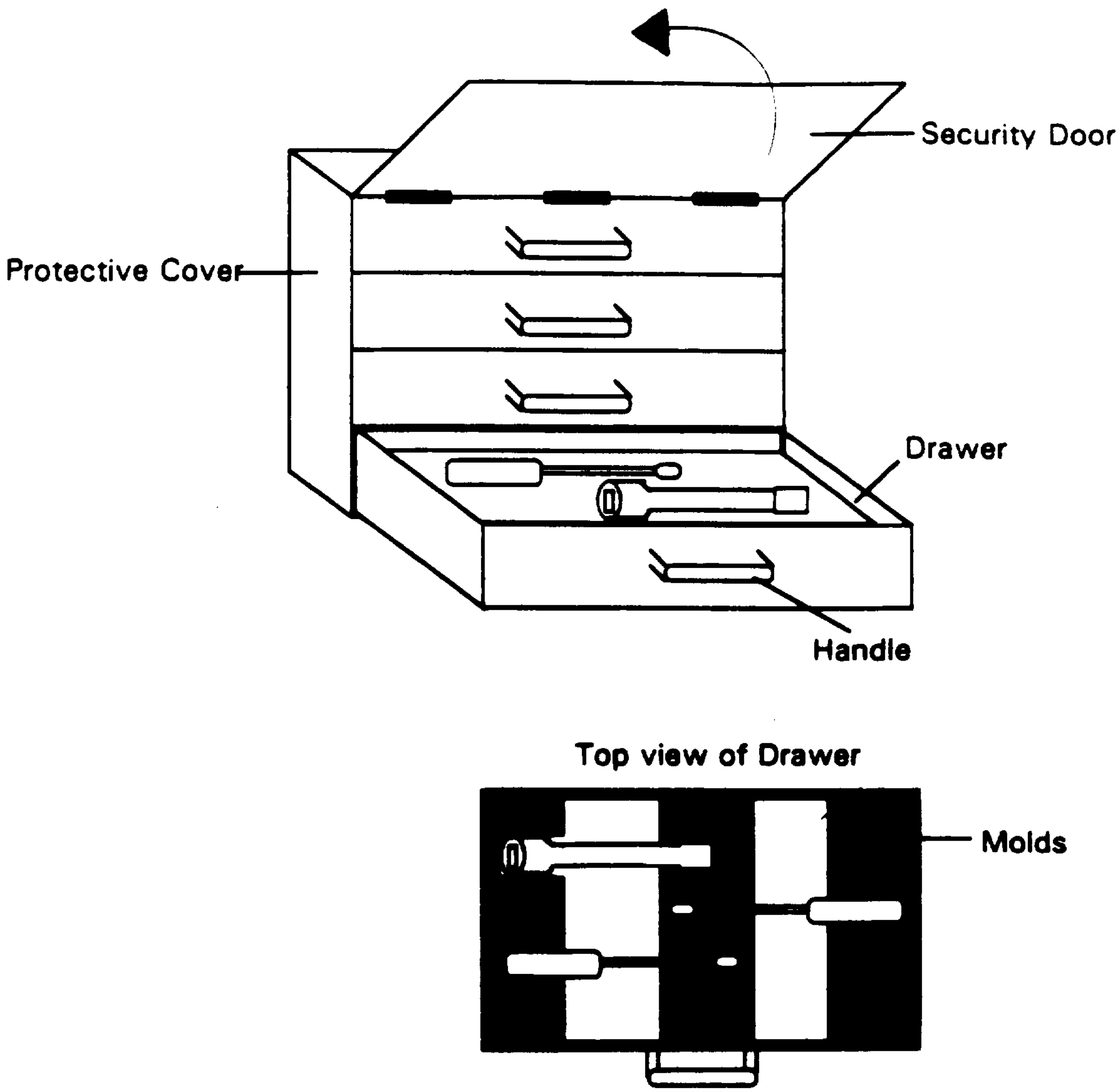


Figure 5. Concept Varient Number One.

Although the drawer concept minimizes the number of elements, it has a few disadvantages to other concepts. The user has to touch the toolbox when removing or replacing a tool. As a result, the contact time of the user with the box is increased. This concept wastes space because the drawers have to provide the 6 cm clearance around the tool.

Concept Variant 2: Conveyor

The second concept variant utilizes the principle of a conveyor as shown in Figure 6. The tools are located in the device through an open window. The window will remain open until the roll-top secure door is latched for landing. The opening serves as a functional combination of positioning the tool for access and exposing the tool for the astronaut to grasp. The conveyor will move rotationally by means of a crank operated by the astronaut. This crank will be a removable modular part to minimize the volume during take off and landing and reduce the likelihood of injury to the EMU.

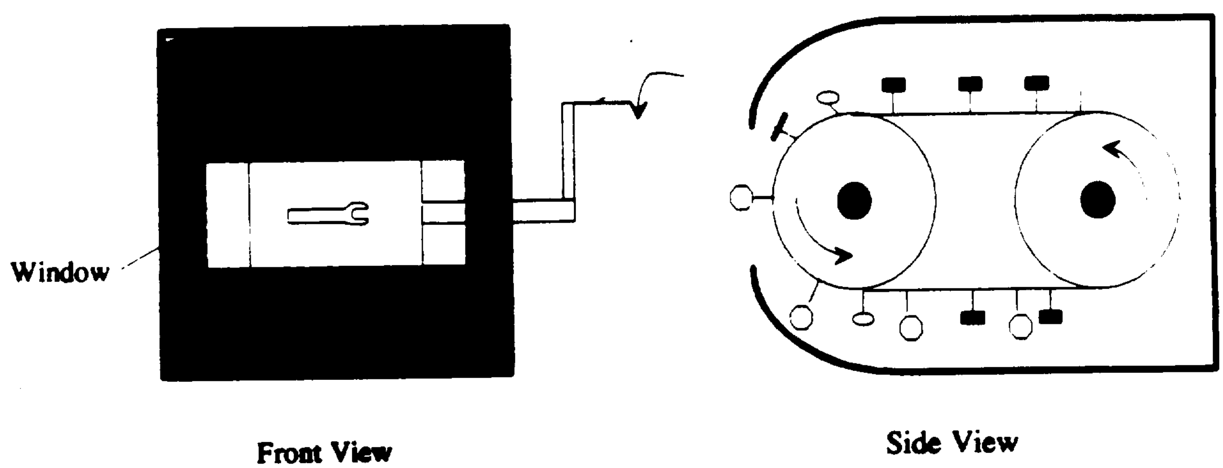


Figure 6. Concept Variant 2

The tool storage device will be protected by a hard cover. The cover has a rectangular end for attachment to the EAPC while the protruding end of the container is an oval shape. The oval shape of the device provides three functions. The volume occupied by the device is minimized by rounding the end of the container. Calculations in

Appendix D indicate a volume of 97 meters cubed for a rectangular container whereas the estimated volume for the rounded container is 84 meters cubed. Furthermore, the rounded end will eliminate stress concentration points in the container that would otherwise occur in the corners of a rectangular box. Finally, the rounded device will eliminate sharp edges that could harm the EMU suit. The tools inside the device will be held securely in place by clips.

The primary concept in this design is the conveyor. As the tools move around the radial part of the conveyor, the clearance between each tool is expanded to 7.3 centimeters. The conveyor is coupled with the crank because both elements use rotational movement. The clips attached to the conveyor provide the 6 centimeter clearance on all sides of the tools as specified by NASA standards. A hard cover is used to protect the tools and the mechanisms used to rotate the tools. The open window locates the tool's position and exposes the tool for access; therefore, these functions are combined into one operation. The roll-top door protects the tools while the device is stowed for transport.

One of the most important advantages of the conveyor system is minimal contact with the tool storage device without the use of an outside energy source. In the conveyor system, the only element that the astronaut must contact is the crank to rotate the system. Other advantages include minimization of volume required to hold the tools and clearances around each tool that exceed NASA standards.

A disadvantage of the conveyor system is that the time to retrieve and replace tools is increased due to the slow rotation of the conveyor. In addition, positioning the astronaut so that he/she can crank the system and observe the open window simultaneously could be difficult. Moving parts may be exposed during operation of the device because of the open window. Exposed moving parts in the system could harm the EMU suit or the astronaut.

Concept Variant 3: Electronic Tool Storage Device with Robotic Arm

The design for the third concept variant is an attempt to fully automate the process of retrieving and replacing a tool as illustrated in Figure 7. By automating the process as much as possible, the device itself will perform all the required subfunctions and the contact time between the device and the astronaut's hand will be minimized.

The third concept variant includes the use of a computerized mechanism (robotic arm) that retrieves and replaces the tools. The astronaut selects the desired tool to be replaced or retrieved by inputting a code into a number pad located on the exterior of the tool storage device. Each code represents a preprogrammed path the robotic arm follows to the selected tool. The robotic arm receives the signal and moves in the predetermined

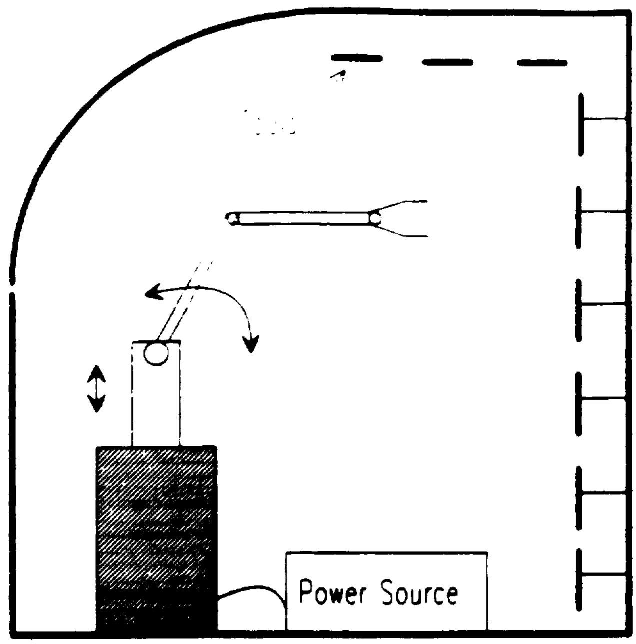


Figure 7. Concept Variant 3.

path to the tool's location, grips the tool, and carries the tool to the opening. The device opens while the robotic arm is in motion in order to decrease the process time. The robotic arm will extend to the end of the device closest to the astronaut's workspace to allow the astronaut to grab the tool. The tools will be secured inside the device with clips. The tools will be closely aligned on the interior of the tool storage device's walls. The robotic arm does not require large clearances to grasp the tools; therefore, the space to store the tools is minimized.

The robotic arm is driven by an electrical system using a DC current (Nof, p. 55). The electrical system is operated by two 200 W radio-isotope thermoelectric generators (RTG) (Norrell). The generators also provide enough power for the computerized number pad to send the signals to the robotic arm.

The solution principles in variant 3 were combined to minimize the amount of contact time between the astronaut's hand and the device. Cost and complexity of design issues were not considered. The number pad provides a label to indicate the tool's position. The number pad sends a signal to the robotic arm which is a system of levers. Since the path of the robotic arm includes a rotational movement, the most efficient way to minimize the volume and protect the device is with a curved shell. In order to expose the tool, a roll top door is used because it is compatible with the curved surface. The tools are secured by clips because clips will allow the tools to be stored close together.

The primary advantage of concept variant 3 is the minimization of contact time between the astronaut and the storage device. The only object the astronaut contacts is the number pad and the outside shell of the device is never touched. The time to retrieve or replace a tool is minimized because indicating the tool's position, orienting the tool for access, and exposing the tool are occurring simultaneously. Clearances between tools required by a robotic arm are small in comparison to those required by an astronaut's glove. The volume to store tools for the robotic arm concept is reduced.

Concept variant 3 has several disadvantages. For example, the device requires an external energy source. The power level must be indicated to ensure adequate energy levels during use. Associated with an external power source is an increase in the number of components in the design. Increasing the number of elements in the design raises the amount of maintenance and cost of production. Furthermore, the device requires the use of sensitive equipment for which proper protection from the harsh environment is essential. The protective shell for the container must maintain an interior temperature range between -10°C to 60°C (Nof, pp. 552-556). The temperature inside the protective shell must be monitored and a signal must indicate if the temperature has exceeded the operational temperature range.

Feasibility

To establish whether the concepts are feasible, criteria was set to evaluate each concept. These criteria are: the time the user contacts the device, the volume of the device so that all tools are contained, and the forces required to operate the tool storage device. Volume minimization is a customer requirement and is an important geometrical constraint for two reasons. First, two of the dimensions have already been defined in the problem statement by the interfacing with the EAPC. The third dimension which extends out from the payload wall is the variable. The tool storage device must not protrude so as to interfere with astronaut's working area. In addition, on Earth the weight of the device will create a torque acting to pull the EAPC from the payload wall as seen in Figure 1. The time to operate the storage device is also a customer specification of under 30 seconds. If the estimated time to operate the device exceeds this limit, the concept variant can automatically be eliminated. Due to the limitation of range of motion imposed by the EMU, there is a loss in dexterity and agility in space. The forces required to operate the storage device cannot exceed NASA ergonomic specifications of 3.95 Newton-meters of torque and 156 Newtons for opening drawers (NASA, p. 11-12).

Feasibility Concept Variant 1

The feasibility of the drawer system is evaluated using the predetermined feasibility criteria. Appendix E contains the calculations of the volumetric requirements. The box would be approximately 0.7 cubic meters. This approximation was made assuming that the box had four drawers that are 15 centimeters deep to provide the needed clearances around the tool. Each drawer holds 16 tools. The width is 114.3 cm, the length is 96.5 cm, and the depth is 63.5 cm. Because the estimated volume of the box holds all tools, the feasibility criteria for the volume and containing all tools is met.

A drawer must require less than 156 Newtons of force exerted by the astronaut to open or close the drawer. The force applied to open and close a drawer on Earth will serve as a comparison to the force required in space. The force required in space is less due to microgravity conditions. If the force required on Earth is less than 156 Newtons, this concept meets the feasibility criteria. Appendix C shows a rough calculation of the force required on Earth. Assuming that each drawer contains 16 tools that weigh 9 Newtons and the coefficient due friction (μ is 0.2) the force required to open or close the drawers is 37 Newtons. This required force does not exceed 156 Newtons; therefore, this concept meets this feasibility criteria.

The time the astronaut is in contact with the storage system must be less than 30 seconds. Seven seconds are required to open the box, retrieve the tool, and close the box. Appendix C contains the estimations of the contact time. Since the astronaut will be in contact with the device for approximately seven seconds, the 30 second time limit is not exceeded, and the feasibility criteria is met.

Feasibility: Concept Variant 2

Calculations for the conveyor concept variant can be found in Appendix D. The first calculation made was an estimate of the volume required to contain all of the tools. The volume was estimated using two conveyors in the system. The volume calculated was

0.7 meters cubed. Assuming that the gear ratio used in the device is 2:1, the approximated length of the crank needed using the ergonomic limitation of 3.95 Newton-meters of torque is 25 cm. In order to estimate the time required to retrieve a tool, calculations of radial velocity were made according to the estimated dimensions of the conveyer. The time of complete rotation was then divided by two based on the assumption that on average, an astronaut will only have to rotate the conveyor half way to find the tool he/she wants. An additional 3 seconds was added to account for the time to reach into the box and unclasp the desired tool. The total tool retrieval time is 20 seconds. The time of retrieval, while large in comparison to the first concept variant, is still under the 30 second limitation.

Feasibility: Concept Variant 3

The first calculation made to determine the feasibility of the robotic arm was the estimated volume of the tool storage device. The base of the robotic arm is estimated to be 50 cm by 50 cm by 50 cm, with a robotic arm length of 70 cm. The estimated required volume of the tool storage device is 0.581 meters cubed. Calculations for concept variant 3 can be found in Appendix E. This volume includes one side that effectively interfaces with the EAPC. Next, it was determined if all the tools would fit into the tool storage device. The robotic arm can grasp a tool with a clearance of only .5 cm (Nof, p. 73). Under these low clearance conditions, the tools can be clipped to the interior of the device with the dimensions of 114 cm by 64 cm by 80 cm. The next consideration in the feasibility study is the amount of force required by the astronaut to operate the device. Since the device is fully automated, the required force by the astronaut is minimized. The only force required by the astronaut is to press the button indicating which tool is desired. This operation requires a force of 2 kilograms which is less than the 12 kilogram force that can be required to push a button (Van Cott, p. 560). Another consideration is the total time it takes to retrieve or store a tool. The estimated time for the entire process of retrieving or replacing the tool is seven seconds as calculated in Appendix E. Contact time and process time is minimal so the device is feasible. An additional feasibility check on concept variant 3 was added to ensure safety. This device will require an energy source. The robotic arm uses approximately 300 Watts of power and 300 Volts (Nof, p.556) which will produce a current of 1 ampere, shown in Appendix E. This is a reasonable amount of current to be produced (Norrell), so the device is feasible.

Design Decisions

Decision Matrix

The decision matrix is used to compare the three concept variants Five categories were used to evaluate the tool storage device. ergonomics, design, tool protection, geometry, and heat transfer. These categories evolved from the customer requirements Ergonomics is used to evaluate these concepts because the astronaut's range of motion available while wearing the EMU is limited. The complexity and cost of the design need to be evaluated because a design with many components may require more engineering time and high precision manufacturing processes. Tool protection prevents damage to the tools from the surrounding environment; hence, the life of the tools may be prolonged. The geometry of the device affects the amount of workspace available to the astronaut. As the amount of heat transfer from the astronaut's hand to the device increases, the heat loss from his hand causes a decrease in dexterity.

In order to determine the weights assigned to each criteria, a dominance matrix in Table 5 was used. Relative weights were established by comparing two categories at a time and assigning a value of 0 or 1 where 1 represents the dominate category. The five main categories were then subdivided into fourteen specific issues. A dominance matrix was again used to assign relative weights to the fourteen subcategorize. Table 6 illustrates the matrix application.

Table 5
Dominance Matrix 1

Category	Ergonomics	Design	Tool Protection	Geometry	Heat Transfer	Total
Ergonomics	X	1	1	1	1	4
Design	0	X	0	1	0	1
Tool Protection	1	1	X	1	1	4
Geometry	0	1	0	X	0	1
Heat Transfer	0	1	0	1	X	2

Table 6
Dominance Matrix 2

Category	Cost	Complexity	# steps	Time	Clearance	Safety	Ext. Mat'l	Secure	Exposure	Mat'l	Contact Time	Mass	Volume	EAPC Comp	Total
Cost	X	1	0	0	0	0	0	0	0	0	0	0	1	1	3
Complexity	0	X	1	1	1	1	1	1	1	1	0	1	1	1	13
# of steps	1	0	X	0	1	0	0	0	0	0	0	0	1	1	4
Time	1	0	1	X	1	1	0	0	0	1	0	1	1	1	8
Clearance	1	0	1	0	X	0	0	0	0	0	0	0	1	1	4
Safety	1	0	1	1	1	X	0	0	0	1	0	1	1	1	8
External Mat'l	1	0	1	1	1	1	X	1	0	1	0	1	1	1	10
Securing Tool	1	0	1	1	1	1	1	X	0	1	0	1	1	1	10
Exposure	1	0	1	1	1	1	1	1	X	1	0	1	1	1	11
Material	1	0	1	0	1	0	0	0	0	X	0	0	1	1	5
Contact Time	1	1	1	1	1	1	1	1	1	1	X	1	1	1	13
Mass	1	0	1	1	1	1	0	0	0	1	0	X	1	1	8
Volume	0	0	0	0	0	0	0	0	0	0	0	0	X	1	1
EAPC Comp.	0	0	0	0	0	0	0	0	0	0	0	0	1	X	1

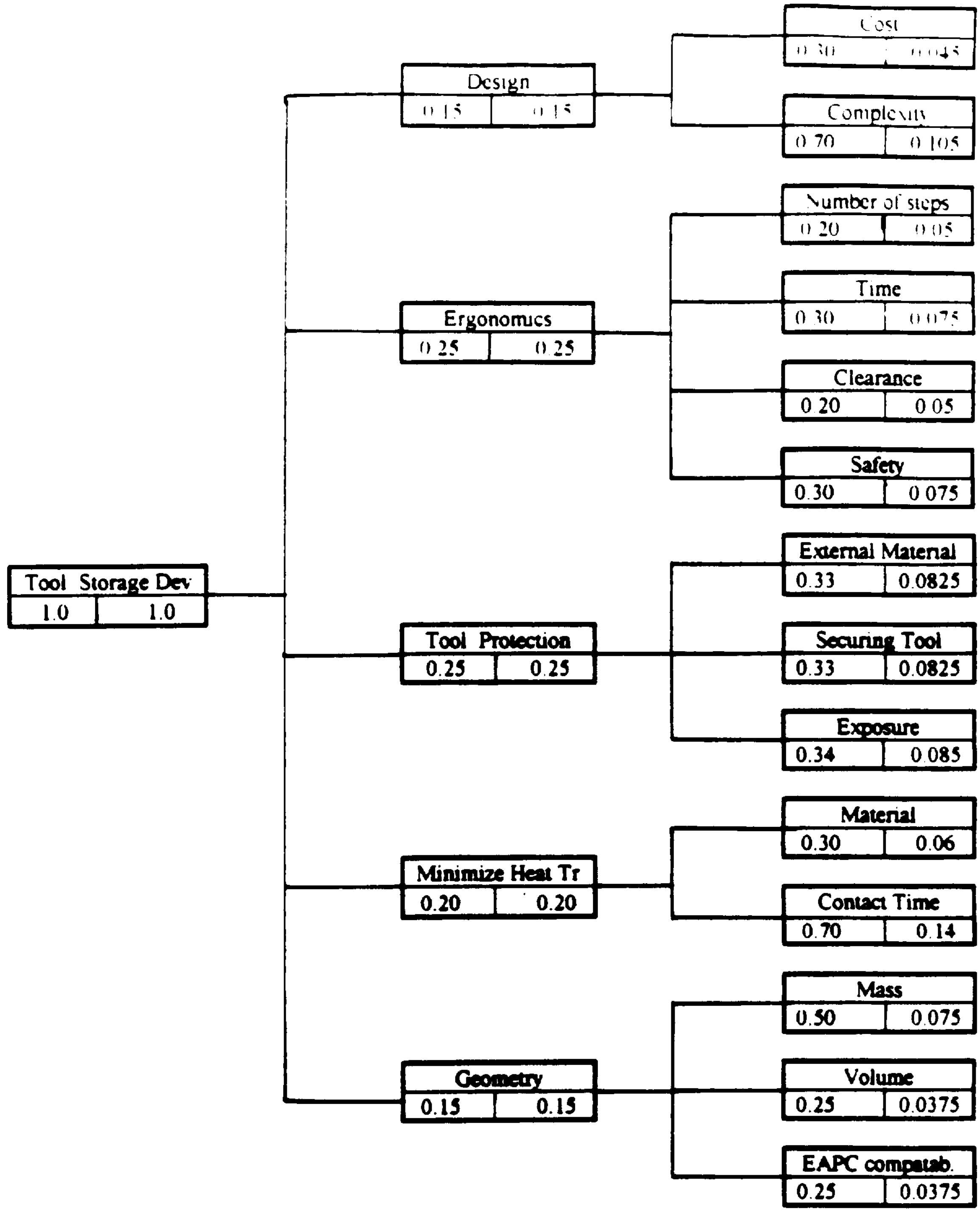


Figure 8. Decision Matrix Weight Distribution.

The highest ratings in the dominance matrix were ergonomics and tool protection. Since ergonomics and tool protection are the primary functional requirements, it is expected that they would receive a high rating. As ergonomics and tool protection were compared to the other categories they were found to be dominate in almost every case.

Figure 8 shows the distribution of the weights among the categories and sub-categories. The value on the left represents the weight assignments within a category. The value on the right is the overall weight of the sub-categories with respect to the total.

Evaluation of Concept Variants

Every concept variant was given a score for each of its categories on a scale of 0 to 100. The scoring scale shown in Table 7 was used to evaluate each concept variant uniformly. A category score was obtained by multiplying the score and the weight. The overall concept variant score was the sum of the category scores. The overall score was then a reflection of the performance of the concept variant based scoring in each category and the category's weight of importance to the design.

Table 7
Scoring Criteria

Excellent	100
Very Good	85
Good	70
Average	55
Poor	40
Unacceptable	30

Table 8 contains the justification for the scores for each concept variant. When a category was quantified, the scores were based on how the concept variants fulfilled the specifications. When quantification of a category was not possible, as in the case of mass or cost, the grade was assigned on the basis of how the concept variants compared to each other. Some categories used calculations to support scoring decisions. For example, an

Table 8
Characteristics of concept variants

Category	Concept Variant 1	Concept Variant 2	Concept Variant 3
Number of Steps	5 steps (locate, open, reach, release,close)	3 steps (rotate, reach, release)	2 steps (input, release)
Time to Retrieve	7 seconds	20 seconds	6 seconds
Clearance	Wasted space, drawers must be deep	Orientation of rotating belt provides clearance at release point	No 3" clearance needed, robotic arm retrieves tool
Safety	Sharp corners, number of steps	Moving parts	Power needed, high maintenance
Cover Material	Tool well protected, outside cover and drawers	Stress concentration reduced. Tools move constantly	Robotic arm needs more protection than tools themselves
Securing Tools	Clips, molds	Handles, clips	Handles, clips
Exposure	Short exposure, only few tools at the time	Permanent opening, part of rotating mechanism always exposed	Sensitive equipment exposed, large opening
Contact Time	Time to open and close drawer	Contact with crank at all times	Contact with number pad only
Material	Same	Same	Same
Mass	Drawers, structure, handles	Belts, gears, structure	Structure, clips, robotic arm system
Volume	0.75m^3	0.70m^3	0.70m^3
EAPC Compatibility	Direct	Avoid external parts	Sensitive equipment

approximate volume for each concept was calculated accounting for the size of the tools and the clearances required for tools access. Simulations performed on mechanisms with similar systems provided approximate calculations to score the concepts. To estimate the time to open a drawer, an experiment was conducted to measure the time required to open a drawer in a kitchen. Numerical calculations are presented in Appendices C, D, and E, while the thought processes for certain categories is presented below.

Time to retrieve or return tools. The estimated time to retrieve a tool for concept variants 1 and 3 is 7 seconds. Since NASA has established a maximum retrieval time of 30 seconds, these two concept variants are rated very well. The rotating conveyor takes a longer time to retrieve tools because the astronaut must rotate the tools around the circumference of the conveyor and was given a rating of 70.

Clearance. Concept variant 3 has an advantage over the other concept variants because a clearance of only 0.5 cm is required for the robotic arm to retrieve and return tools. For this reason concept variant 3 is rated excellent. The drawer arrangement is rated as average because the tools must be raised from the bottom of the drawers 6 cm to comply with NASA standards for clearance. The conveyor system is rated as very good since the clearance needed is provided as the tools pass over the end radius of the conveyor belt.

Exterior Material. The requirements for the external material of each device is different due to the varying sensitivity of internal parts. For example, concept variant 3 has much more rigorous requirements than the toolbox design because the robotic arm has more sensitive equipment.

Exposure to Environment. The drawer system rating is excellent in this category. The tools are exposed to the environment only when a drawer is open. In addition, few tools are exposed to the environment at one time. The conveyor system is rated good since some of the tools are always exposed due to the opening.. The robotic arm system has an average rating because the robotic arm is exposed when the door opens to expose the tool to the user.

Contact Time. The robotic arm is considered excellent with respect to contact time. The only time the astronaut contacts the system is when the user enters the code on the number pad. The drawers are considered very good because the astronaut only touches the system to open and close the drawers. Finally, the conveyor system rates good because operation of the crank requires the astronaut's contact..

Mass. Since concept variant 3 includes a power source and the robotic arm, this system has the most components and therefore the largest mass. The other two systems have similar masses. The drawer arrangement has a slightly lower score because the toolbox requires material for the protective shell and the molding in the drawers. On the other hand, the conveyor only requires materials for the external covering and the rotating belt.

Complexity. In this category the highest score was assigned to the toolbox because the device operates in one plane of transitional motion and has the lowest expected maintenance requirements. It is sufficient to design one drawer to get a design for the entire device. As a result, this device is rated as excellent. The rotating conveyor is considered very good. The conveyor requires gears to create mechanical advantages. Finally, the automatic system is rated poor. The design of this device involves electronics, development of supporting software, and introduction of a power source. These factors make the design of the concept variant complex.

Evaluation and Recommendations

The results of the evaluation for each concept variant is presented in Table 9. The total score for the drawer system is 87, the score for the conveyor system is 84.5, and the score for the electronic system is 72. The margin of error for this matrix is ± 5. If one or more of the constraints are relaxed, these scores may change; thus, these results are not absolute. Because two of the scores are within a margin of error of one another, we recommend that the drawer arrangement and the conveyor be taken into the next steps of the design process. At this point, the best concept is not clear. Further analysis of the components of each design will provide more data to select the best concept.

Table 9
Results of the Decision Matrix

Criteria	Design		Ergonomics				Tool Protection			Heat Transfer		Geometry			
Category	Cost	Complex.	Steps	Time	Clearan.	Safety	Material	Securing	Exposure	Material	Time	Mass	Volume	EAPC	TOTAL
Weight	0.045	0.105	0.05	0.075	0.05	0.075	0.0825	0.0825	0.085	0.06	0.14	0.075	0.0375	0.0375	1
Concept															
Drawers	80 / 3.6	82 / 8.61	70 / 3.5	87 / 6.53	65 / 3.25	80 / 6	100 / 8.25	95 / 7.83	95 / 8.08	85 / 5.1	85 / 11.9	85 / 6.37	90 / 3.38	95 / 3.56	87
Conveyor	95 / 4.28	85 / 8.92	90 / 4.5	70 / 5.25	92 / 4.6	90 / 6.75	87 / 7.18	95 / 7.83	80 / 6.8	76 / 4.6	78 / 10.92	92 / 6.9	75 / 2.81	85 / 3.19	84.5
Robotic Arm	35 / 1.57	35 / 3.68	90 / 4.5	85 / 6.38	100 / 5	95 / 7.13	60 / 4.95	95 / 7.83	55 / 4.67	60 / 3.6	95 / 13.3	55 / 4.13	80 / 3	60 / 2.26	72

Conclusions and Future Work

Hand tools are important to the success of space flight, particularly on recent mission which have aimed at repairing existing equipment. In EVA, heat transfer between astronauts and objects they contact is a major design issue due to the extremely cold temperatures. Limitation of astronaut-equipment contact is beneficial to the astronaut's comfort and dexterity. The design of a zero gravity tool storage device for the Shuttle bay must accomplish three main functions: securing the tools in position, protecting the tools from the space environment, and minimizing the contact time between the astronaut and the device. This proposal highlighted customer and design specifications to be considered for the space mission, a functional description of the processes of the tool storage device, possible solution principles for the most important subfunctions, and three concept variants. The final section of the proposal tests the three concept variants for feasibility and evaluates them based on a decision matrix.

Two of the proposed concept variants resulted in acceptable scores within uncertainty of one another in the decision matrix. It is recommended that both concept variants be taken through the embodiment stage of design until one variant illustrates superior characteristics. Deciding factors in the embodiment design might be deduced from the material constraints. For example, in order to make the tool storage device large enough to hold the tools and with adequate strength properties, the design might exceed the 1045 Newtons weight limit. The drawer design includes moldings constructed of a highly elastic polymer. Obtaining a polymer which does not allow gases to escape in the near-vacuum conditions of space could be impossible, in which case alternatives such as clips would have to be explored. Substantial differences in cost could also indicate a preferable concept variant. The cost of materials to meet the required structural constraints could limit the production of one variant. The cost of manufacturing the device could also be a concern. Intricate moldings found in the drawer design will likely require a machining process which is the most expensive manufacturing method.

Many detailed design issues have not been addressed in the scope of this paper but can at this points be identified. For example, stops to limit motion should be incorporated in both designs. Since there are no opposing gravitational forces acting to stop motion, inertial forces become an important design issue in space. Handles and foot rests will also need to be included in the final embodiment design.

In this preliminary analysis, concept variants one and two were deemed acceptable according to our criteria. In reality, these concepts may not be practical solutions to the problem. Because this analysis was limited to three concept variants, other possible solutions were unable to be explored. After further exploration of possible solutions, the best solution can be determined.

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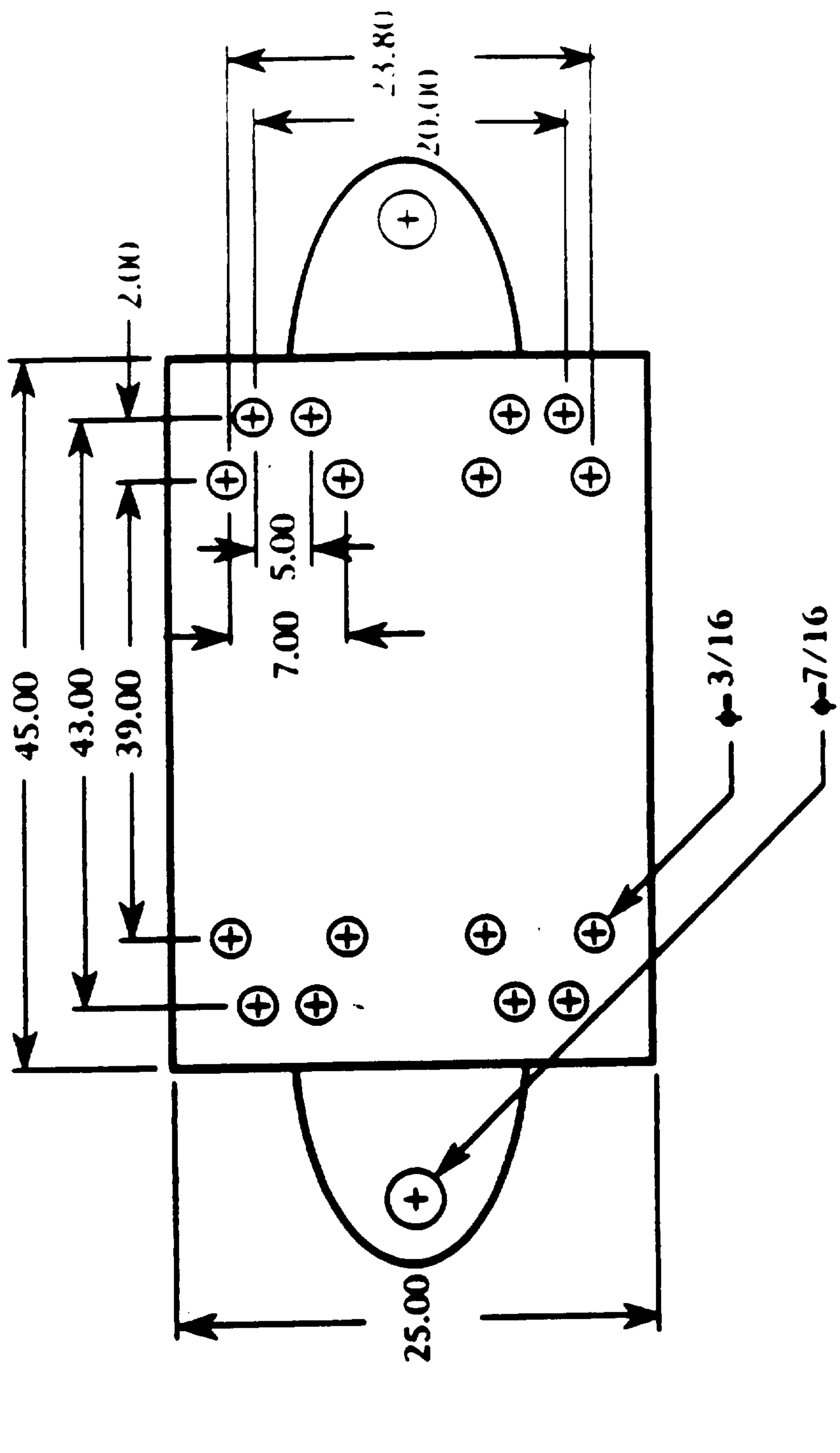
Dimensions of the EAPC



Appendix B

Tool List

Description	Quantity
5/16 inch rigid hex capture tool, 10.3 in	2
5/16 inch wobble hex capture tool, 10.3 in	2
5/16 inch wobble socket, non-capture, 7.3 in.	2
5/16 inch wobble socket, non-capture, 10.3 in.	2
7/16 inch and 1/2 inch box end wrench	1
7/16 inch open end ratcheting wrench	1
7/16 inch rigid hex capture tool, 10.3 in.	2
7/16 inch wobble hex capture tool, 10.3 in.	2
Caddy with french hooks	2
Coax connector tool, hex	2
Coax connector tool, hex with shoulder	2
Coax connector tool, round	2
D-connector mate tool	2
Electric connector pin straightner multi-size	2
D-connector demate tool, external	2
D-connector demate tool, internal	2
3/8 inch drive mcgether ratchet	2
Mechanical finger, EVA	1
Right angle drive tool	1
Shrouded flex screwdriver, 4.8 in.	2
Shrouded flex screwdriver, 8.6 in.	2
Shrouded rigid screwdriver, 3.8 in.	2
Shrouded rigid screwdriver, 8.3 in.	2
7/16 inch wobble socket, non-capture, 3.0 in.	2
7/16 inch wobble socket, non-capture, 7.3 in.	2
7/16 inch socket with 3 inch extension	3
7/16 inch socket with 6 inch extension	3
7/16 inch socket with 12 inch extension	2
7/16 inch socket with 18 inch extension	2
7/16 inch socket with 24 inch extension	2
Drive pre-load unit	1
Torque limiter	4

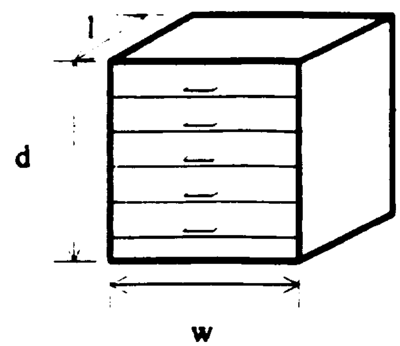
Appendix C

Calculations for Tool Box Concept Variant

The volume of the box is calculated using:

$$V = l \times w \times d$$

where V is the volume of the box, l is the length of the box, w is the width of the box, and d is the depth of the box. Assuming the box has four drawers with 15 centimeter depth each and drawers containing about 16 tools each, the volume is approximately 0.7 cubic meters.

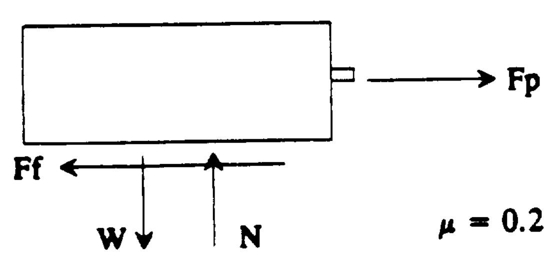


The time the user is in contact with the box is estimated by the time it takes to open the drawer, remove the tool, and close the box. The user will take approximately 7 seconds to complete these tasks. Four seconds are allotted to open and close the box, and three seconds are allotted to remove the tool from the box. This measurement was obtained through simulation of retrieving a tool from a kitchen drawer.

The forces required to pull the drawer open on Earth are approximated using:

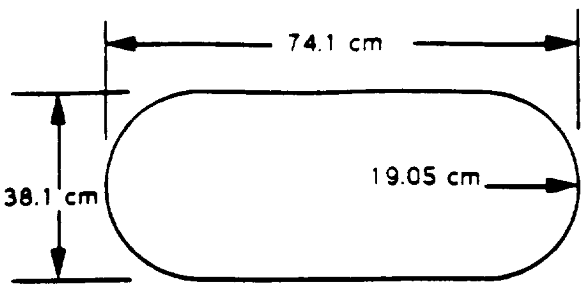
$$F = F_f = \mu \times N = \mu \times W$$

where F is the force required to open the box, F_f is the force due to friction, μ is the coefficient of kinetic friction, N is the normal force, and W is the weight of the drawer including the tools and molds.

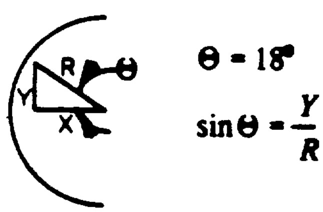


Appendix D
Calculations for Concept Variant 2

Computations of the volume were made by assuming a two-conveyor system with 32 tools on each conveyor. Assuming all of the tools are included with 2.25" clearances, approximate dimensions of the conveyor are below



Using these dimensions, the tools will be 6 cm apart. As the tools pass over the radial end of the conveyor, they will be located at intervals of 18° increasing the distance between tools to 7.3 cm. Trigonometry used in the calculation can be seen below.



$\Theta = 18°$

$\sin\Theta = \frac{Y}{R}$

The total estimated volume of the device is .84 meters cubed.

The time to operate the conveyer was estimated by assuming a linear velocity of 4 inches/second or 10.2 cm/second and dividing by the perimeter of the conveyor. This number was then divided by 2 to take into account that the astronaut will not have to make a complete revolution of the conveyor every time he/she retrieves a tool. Four seconds were also added for the time to grasp and unclamp the tool. The final time calculated was 20 seconds.

Force calculations were made using reverse-engineering. An ergonomic specification of 35 inch-lbs or 3.95 Newton-meters was used and the length of the required crank for operation was then tested for feasibility. To do so, the following equations were used:

w = V/R, where w is frequency, V is linear velocity, and R is the radius of the end.
*gear ratio of 2 was assumed
T = L*F, where T is torque, L is the length, ~~and~~ F is the force.

The resulting length of the crank is 10 cm, which can be considered a reasonable length.

Appendix E
Calculations for Concept Variant 3

Volume V = length * width * height
Base of robotic arm 0.50 m x 0.5 m x 0.5 m
Base of device that interfaces with EAPC 1.143 m x .635 m
Area required to secure all tools: 9920 m^2
Height of device: .8 m
Neglect curved end for these simple calculations
Total Volume: V = 1.143 m * .635 m * .8 m = .6 m^3

Current Needed: I = P/V
The device will use 300 volts
The device will use 300 watts
Current: I = 300 watts/300 volts = 1.0 ampere

Time it takes to Retrieve or Replace a Tool:
Travel 0.70 m : time = .75 sec
Open/Grasp: time = .36 sec
Rotate 120°: time = 4.6 sec
Roll top door opens and closes simultaneously
Total Time: 6 seconds

(Source: Nof, pp 552-556)